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Bar Dynamical Friction and Disk Galaxy Dark Matter Content

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Abstract. I present some new results, from simulations and observations, of the constraints bar pattern speeds place on the dark matter content of disk galaxies.

1. Introduction

Near infra-red images reveal bars in over 50% of disk galaxies (Knapen et al. 2000; Eskridge et al. 2000). The principal dynamical quantity for barred (SB) galaxies is the pattern speed of the bar, Ω_p , usually parametrized by the ratio $\mathcal{R} \equiv D_L/a_B$ (where D_L is the corotation radius and a_B is the semi-major axis of the bar). A bar is termed fast when $1.0 \leq \mathcal{R} \lesssim 1.4$, while, for a larger value of \mathcal{R} , a bar is said to be slow. All measurements of bar pattern speeds have found fast bars (e.g. Gerssen 2002), a result which has been interpreted as evidence for maximum disks in SB galaxies (Debattista & Sellwood 1998, 2000).

2. Bar Dynamical Friction in N -Body Simulations

Fig. 1 plots the evolution of D_L and a_B for a near-maximum disk, and demonstrates that fast bars can survive for a Hubble time in such systems. This simulation used a hybrid grid code, allowing us to achieve much higher resolution than in previous work. At the end of the simulation, which lasted some 44 initial rotation periods of the bar, $\mathcal{R} = 1.3 \pm 0.1$. Although the bar slows down by $\sim 35\%$ in this case, secondary bar growth can still preserve a fast bar in this case. But secondary bar growth has its limitations: for a flat rotation curve, $D_{L1}/D_{L2} = \Omega_{p2}/\Omega_{p1}$, so a strongly braked bar would need to grow ever longer, which, however, makes friction even stronger (Debattista & Sellwood 2000).

Weinberg & Katz (2001) argued that N -body simulations require $N_p \gtrsim 4 \times 10^6$ particles to resolve correctly the bar-halo interaction, while simulations at lower N_p are largely noise-driven. In Fig. 2 I plot the fractional drop in Ω_p between early and late times in a series of simulations in which only N_p was varied. No significant change in the evolution of Ω_p is seen, despite the factor of 100 difference in N_p , suggesting that Weinberg & Katz (2001) have been too pessimistic in their assessment of noise effects. This can be understood by recognizing that a bar slows continuously, so that resonances are broadened. If resonances had been sharp, then indeed large N_p 's would be required, but for broad resonances, more modest N_p 's suffice.

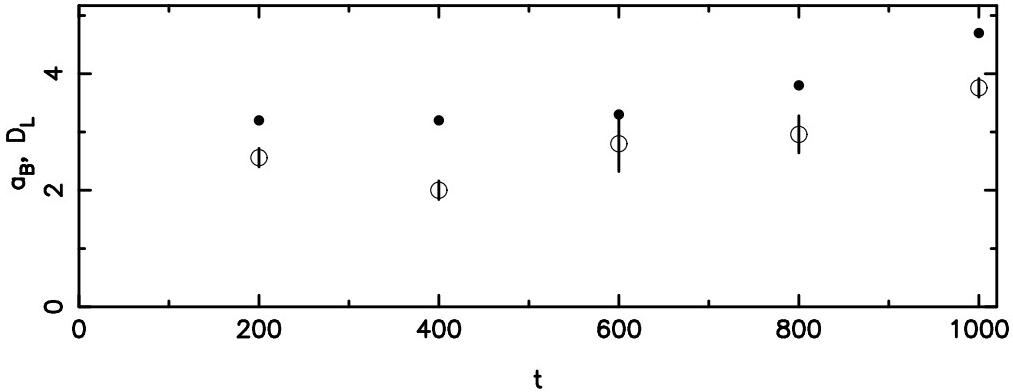


Figure 1. Evolution of a_B (open circles with error bars) and D_L (filled circles) for a massive disk simulation. At $t = 1000$, $\mathcal{R} = 1.3 \pm 0.1$.

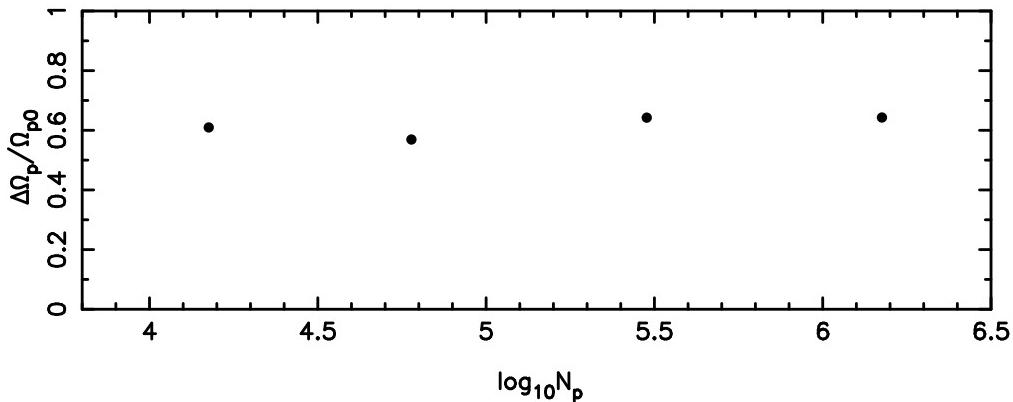


Figure 2. The change in Ω_p , due to halo dynamical friction, between early and late times for a series of simulations in which N_p has been varied by a factor of 100.

3. A Post-Interaction Galaxy

Following Ostriker & Peebles (1973), it is sometimes thought that unbarred (SA) galaxies must be stabilized by massive dark matter (DM) halos; however, bars can also be suppressed by rapidly rising rotation curves (Toomre 1981; Sellwood & Evans 2001). Noguchi (1987) showed that disks stabilized by massive DM halos can still form bars via interactions, and that such bars would be slow. Thus SB galaxies with evidence of past interactions provide a means to statistically test whether SA galaxies are stabilized by massive halos.

NGC 1023 shows evidence of a past interaction (Sancisi et al. 1984), without being at present significantly perturbed. Debattista et al. (2002) measured Ω_p for this galaxy, using the method of Tremaine & Weinberg (1984). The

Tremaine-Weinberg (TW) method is contained in the following simple equation:

$$\Omega_p \sin i = \frac{\int_{-\infty}^{\infty} h(Y) V_{\text{los}}(X, Y) \Sigma(X, Y) dX dY}{\int_{-\infty}^{\infty} h(Y) X \Sigma(X, Y) dX dY} \equiv \frac{\mathcal{V}}{\mathcal{X}} \quad (1)$$

where V_{los} is the line-of-sight velocity, Σ is the surface brightness, $h(Y)$ is an arbitrary weight function, i is the inclination and (X, Y) are galaxy-centered coordinates along the disk's major and minor axes respectively. We obtained 3 slit spectra parallel to the disk's major axis, for each of which we computed \mathcal{V} and \mathcal{X} . Then, plotting \mathcal{V} versus \mathcal{X} gives a straight line with slope $\Omega_p \sin i = 4.7 \pm 1.7 \text{ km s}^{-1} \text{ arcsec}^{-1}$. From the rotation curve, corrected for asymmetric drift, this gives $D_L = 53^{+30}_{-15}''$. Multi-band photometry gives $a_B = 69'' \pm 5''$; therefore $\mathcal{R} = 0.77^{+0.43}_{-0.25}$, consistent with a fast bar. Thus NGC 1023 must have a maximum disk; moreover, if the bar formed in the interaction (which cannot be ascertained), then it cannot have been stabilized by a massive DM halo.

4. Pattern Speed in the Milky Way

As shown by Kuijken & Tremaine (1994), the TW method can also be applied to the Milky Way Galaxy (MWG). For discrete tracers, the TW method becomes:

$$\begin{aligned} \Delta V &\equiv \Omega_p R_0 - V_{\text{LSR}} \equiv \frac{\mathcal{K}}{\mathcal{P}} - u_{\text{LSR}} \frac{\mathcal{S}}{\mathcal{P}} \\ &= \frac{\sum_i f(r_i) v_{r,i}}{\sum_i f(r_i) \sin l_i \cos b_i} - u_{\text{LSR}} \frac{\sum_i f(r_i) \cos l_i \cos b_i}{\sum_i f(r_i) \sin l_i \cos b_i} \end{aligned} \quad (2)$$

where R_0 is the Sun-MWG center distance, V_{LSR} is the tangential velocity of the local standard of rest (LSR), u_{LSR} is the radial velocity of the LSR, $f(r_i)$ is the observational detection probability (which need not be known), $v_{r,i}$ is the heliocentric radial velocity of a discrete tracer, and (l_i, b_i) are its Galactic coordinates. A survey which satisfies the condition of uniform sampling, as required by the method, is the ATCA/VLA OH 1612 MHz survey (Sevenster et al. 1997a,b & 2001), covering $|l| \leq 45^\circ$ and $|b| \leq 3^\circ$. The properties of OH/IR stars make them well suited for Galactic studies. They have bright, maser emission at 1612.23 MHz, which is insensitive to interstellar extinction; the double-peaked profile of the emission permits easy identification; and they are concentrated in the inner MWG, as a result of the Galactic metallicity gradient.

We extracted from the ATCA/VLA OH 1612 MHz survey a sample of ~ 250 OH/IR stars which are older than 0.8 Gyr and have a flux density higher than 0.16 Jy; these criteria give OH/IR stars between ~ 4 and ~ 10 kpc away from the Sun. Applying Eqn. 2 to this sample, as shown in Fig. 3, we obtained $\Delta V = 252 \pm 41 \text{ km s}^{-1}$, where the error was estimated by resampling. If we then assume $V_{\text{LSR}}/R_0 = 220/8 \text{ km s}^{-1} \text{ kpc}^{-1}$ (from SgrA* motion, Backer et al. 1999; Reid et al. 1999 and Cepheid proper motions, Feast & Whitelock 1997) and $u_{\text{LSR}} = 0$ (from SgrA* HI absorption spectrum, Radhakrishnan et al. 1980), we obtain $\Omega_p = 59 \pm 5 \pm 10 \text{ km s}^{-1} \text{ kpc}^{-1}$, where the last error is our estimated systematic error. This Ω_p is consistent with the hydrodynamical simulations of Bissantz et al. (2002), which also require $\mathcal{R} = 1.0 \pm 0.1$.

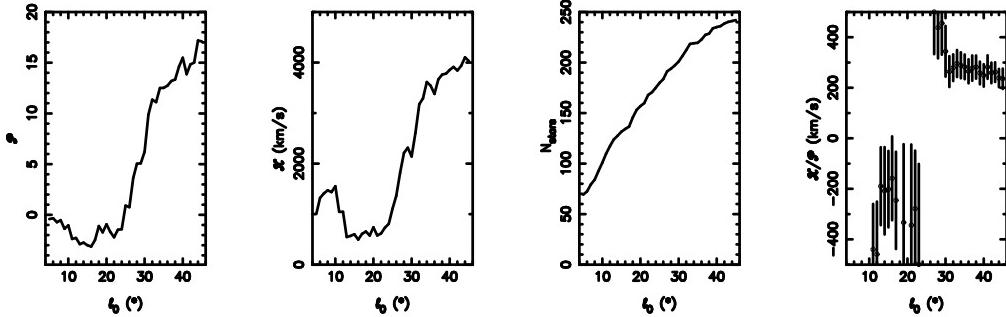


Figure 3. The TW analysis of the OH/IR stars for changing l_0 (the maximum $|l|$ in Eqn. 2). From left to right are \mathcal{P} , \mathcal{K} , the number of OH/IR stars and the resulting \mathcal{K}/\mathcal{P}

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